21cm Intensity Mapping of Baryon Acoustic Oscillations

HI emission at z~1 through cross-correlaton

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BAO - Great Tool for Precision Cosmology

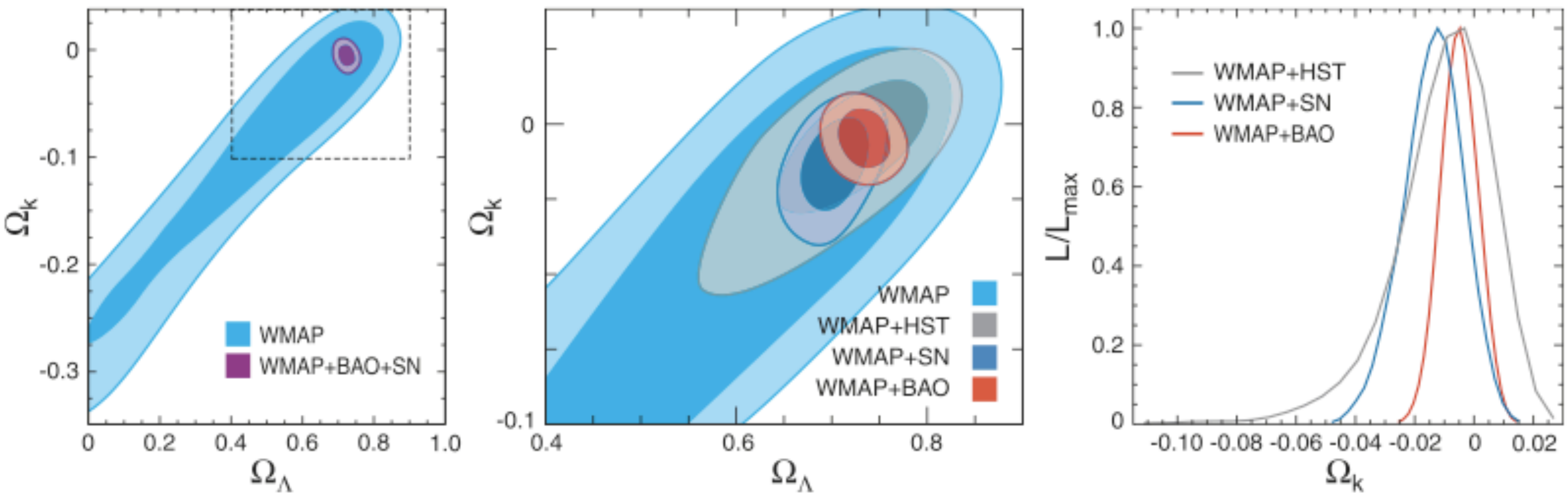


FIG. 6.— Joint two-dimensional marginalized constraint on the vacuum energy density, Ω_Λ, and the spatial curvature parameter, Ω_k (§ 3.4.3). The contours show the 68% and 95% CL. (*Left*) The WMAP-only constraint (light blue) compared with WMAP+BAO+SN (purple). Note that we have a prior on Ω_Λ, $\Omega_\Lambda > 0$. This figure shows how powerful the extra distance information is for constraining Ω_k. (*Middle*) A blow-up of the region within the dashed lines in the left panel, showing WMAP-only (light blue), WMAP+HST (gray), WMAP+SN (dark blue), and WMAP+BAO (red). The BAO provides the most stringent constraint on Ω_k. (*Right*) One-dimensional marginalized constraint on Ω_k from WMAP+HST, WMAP+SN, and WMAP+BAO. We find the best limit, $-0.0181 < \Omega_k < 0.0071$ (95% CL), from WMAP+BAO+SN, which is essentially the same as WMAP+BAO. See Fig. 12 for the constraints on Ω_k when dark energy is dynamical, i.e., $w \neq -1$, with time-independent w.

Komatsu et al. 2008

BAO- Mapping Large-scale Structure

- Current and proposed projects: measure individual galaxy redshifts - BOSS, BigBoss, AAO, HETDEX, WFMOS (optical spectra), KAOS, DES, LSST (photo-z), SKA (21cm), JDEM (space), etc.

- Instead, measure collective large-scale structure traced by HI, without resolving individual objects - Hundreds of galaxies in each BAO pixel : Intensity Mapping (Chang et al. 2008; Wyithe & Loeb 2008).

- $\Delta T = 300\,(1+\delta)\left(\frac{\Omega_{HI}}{10^{-3}}\right)\left(\frac{h}{0.73}\right)\left(\frac{\Omega_m + (1+z)^{-3}\Omega_\Lambda}{0.35}\right)^{-0.5}\left(\frac{1+z}{1.9}\right)^{0.5}\mu\mathrm{K}$

HI BAO Experiment Prospects

- HI Intensity Mapping Experiement: 200m x 200m cylinder telescope

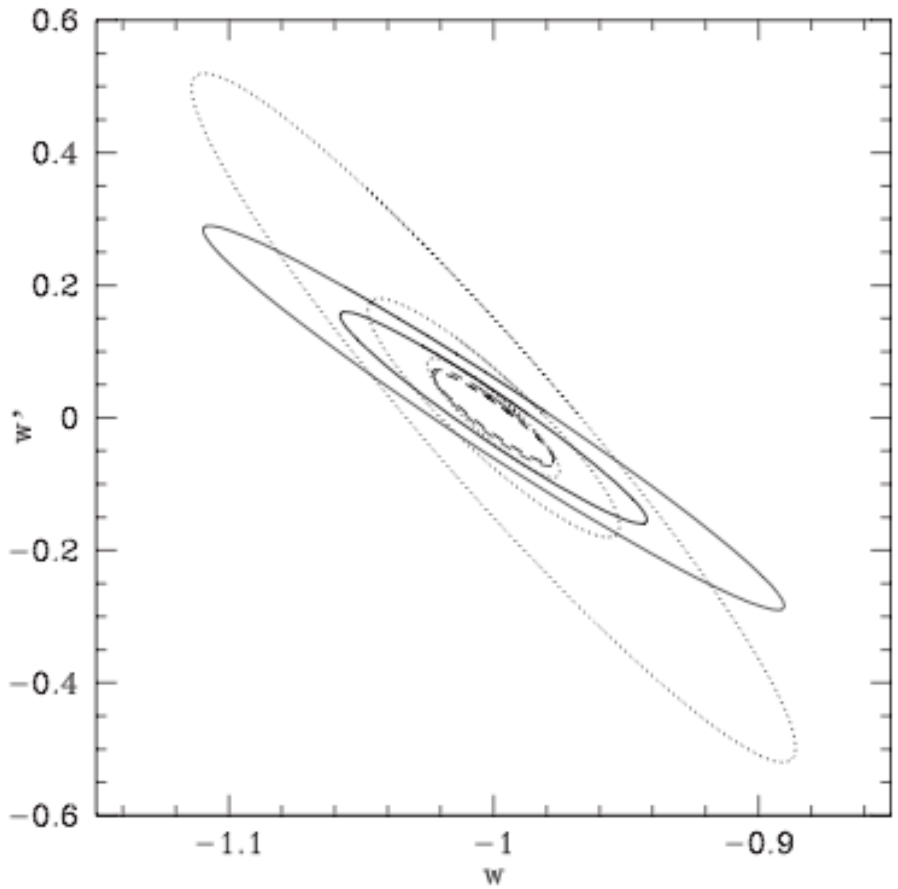


FIG. 4. The $1-\sigma$ contour for IM combined with Planck (inner thick solid for baseline model, outer thin solid for worst case), the Dark Energy Task Force stage I projects with Planck (outer dotted), the stage I and III projects with Planck (intermediate dotted), the stage I, III, and IV projects with Planck (inner dotted), and all above experiments combined (dashed, again thick for baseline, thin for worst case; the two contours are nearly indistinguishable).

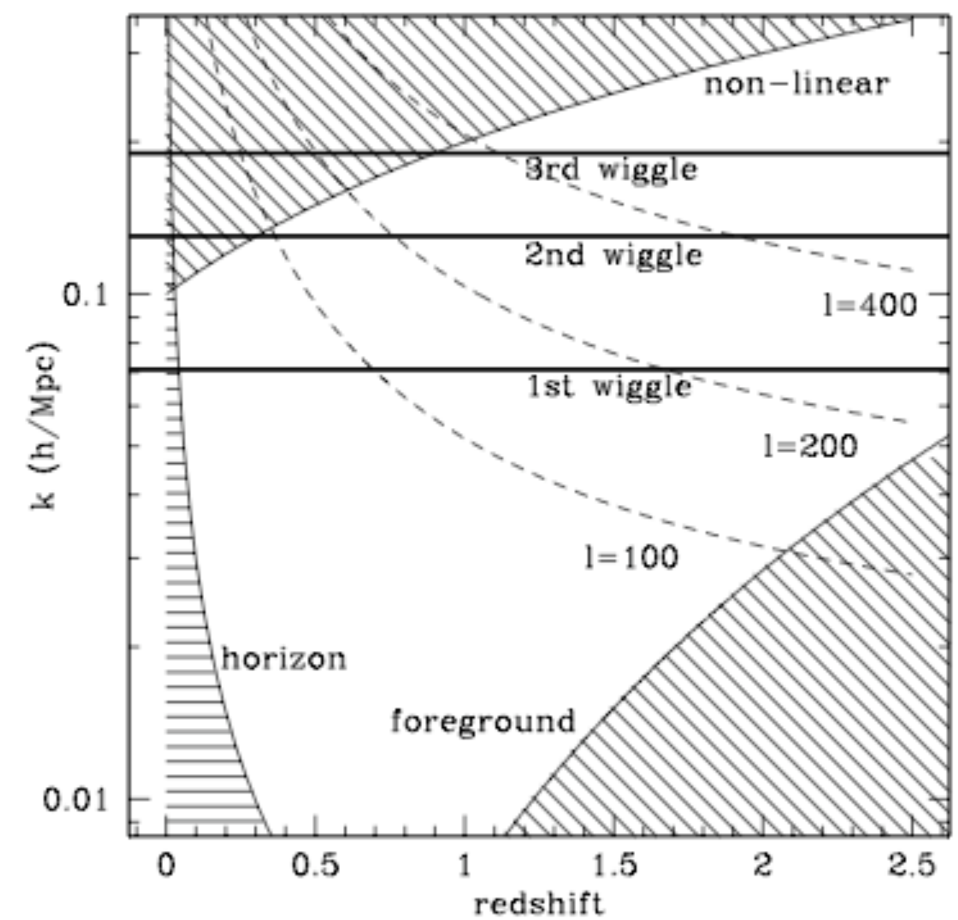


FIG. 3: The observable parameter space in redshift and in scale (k) for BAO. The shaded regions are observationally inaccessible (see text). The horizontal lines indicate the scale of the first three BAO wiggles, and the dashed lines show contours of constant spherical harmonic order ℓ.

Chang, Pen, Peterson, McDonald 2008

HI Intensity Mapping (IM)

- Similar to CMB; large survey area, low surface brightness, but in 3D
- At $0.5 < z < 3$, 350 - 900 MHz:
  - HI signal: 30-300 microK
  - Diffuse foregrounds: Galactic synchrotron $\sim \nu^{-2.6} \sim (1+z)^{2.6}$
    T ~ 3 K, dT ~ 30 mK, but spectrally smooth
    (foreground removal a challenge!)
  - RFI from TV, cell phone, etc.
- IM allows access to much larger distance with existing technology; economical

21cm universe at low-z

- Emitted by neutral hydrogen, ~ 2% of baryons
- HI mostly ionized; neutral fraction ~ 0.01
- Thought to follow LSS; dominated by DLAs (damped Lyman alpha systems)
- Current highest-redshift detected HI emission: z~0.24
- Nature, mass, space density not known, but not important for IM
- Important issues:
  - Is HI really a good tracer of the Large-scale Structure?
  - How much HI there is at z ~1?

How well does HI trace Large-scale Structure?

Cross-correlating HIPASS & 6dFGS Large-scale Structure at $z \sim 0.04$

HIPASS HI Survey

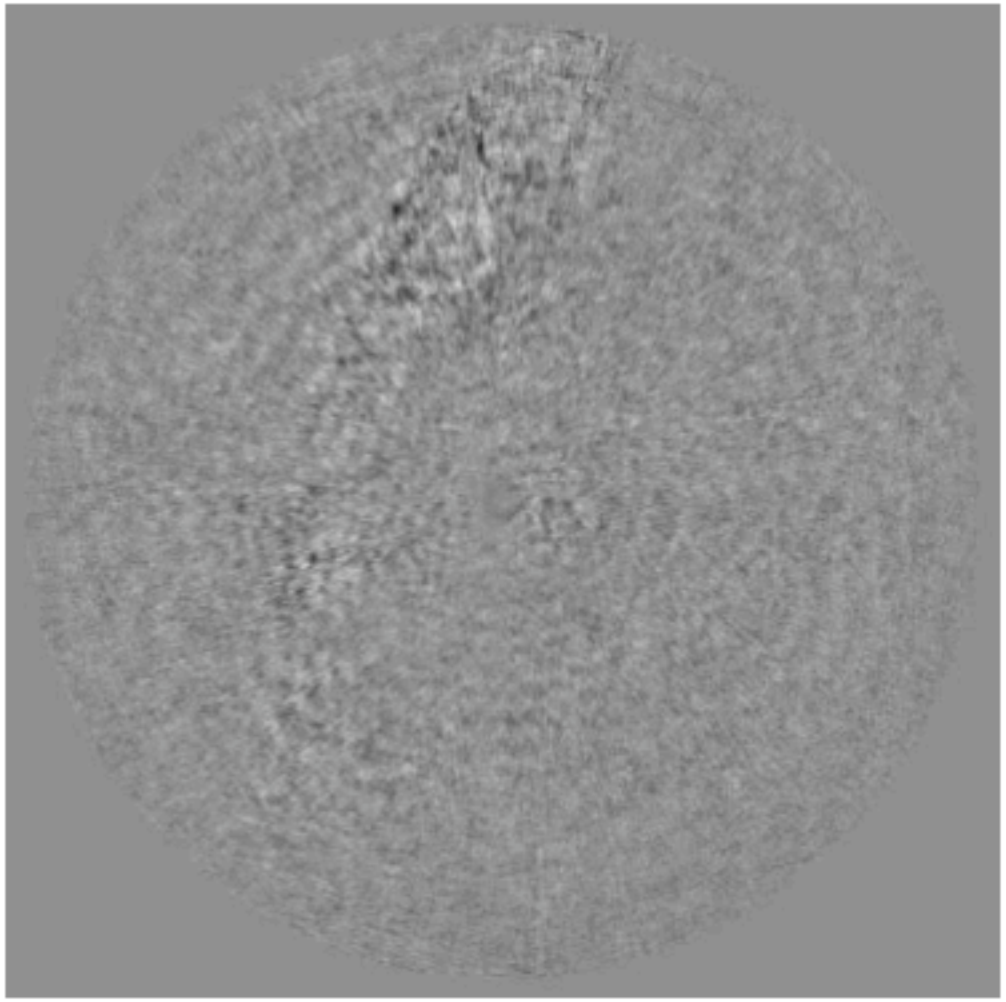


Figure 1. The HIPASS data cube $R < 127h^{-1}$ Mpc, projected in a cartesian coordinate system towards the south pole.

6dF Optical Galaxy Survey

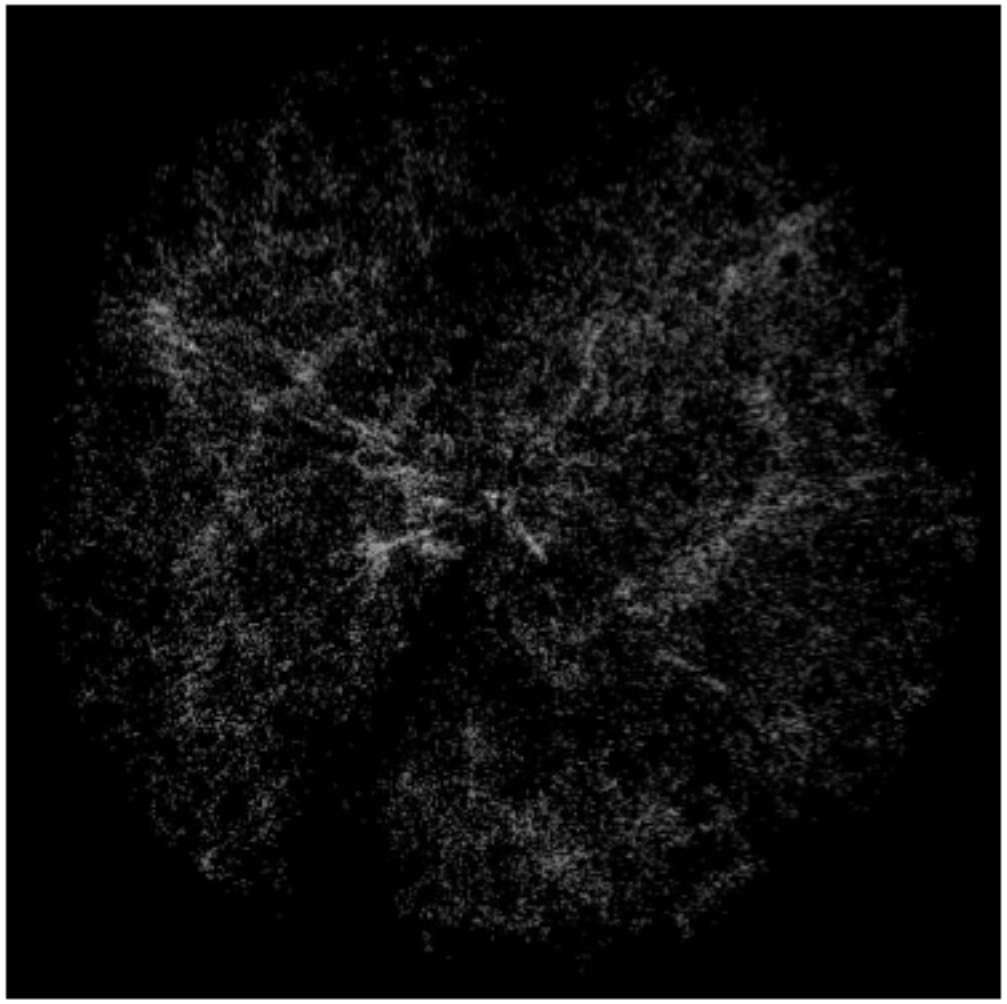


Figure 2. The 6dFGS catalog for $R < 127h^{-1}$ Mpc, also projected towards the south pole. The missing wedges are the galactic plane.

Pen et al. 2008

HI & Optical cross-correlation

Pen et al. 2008

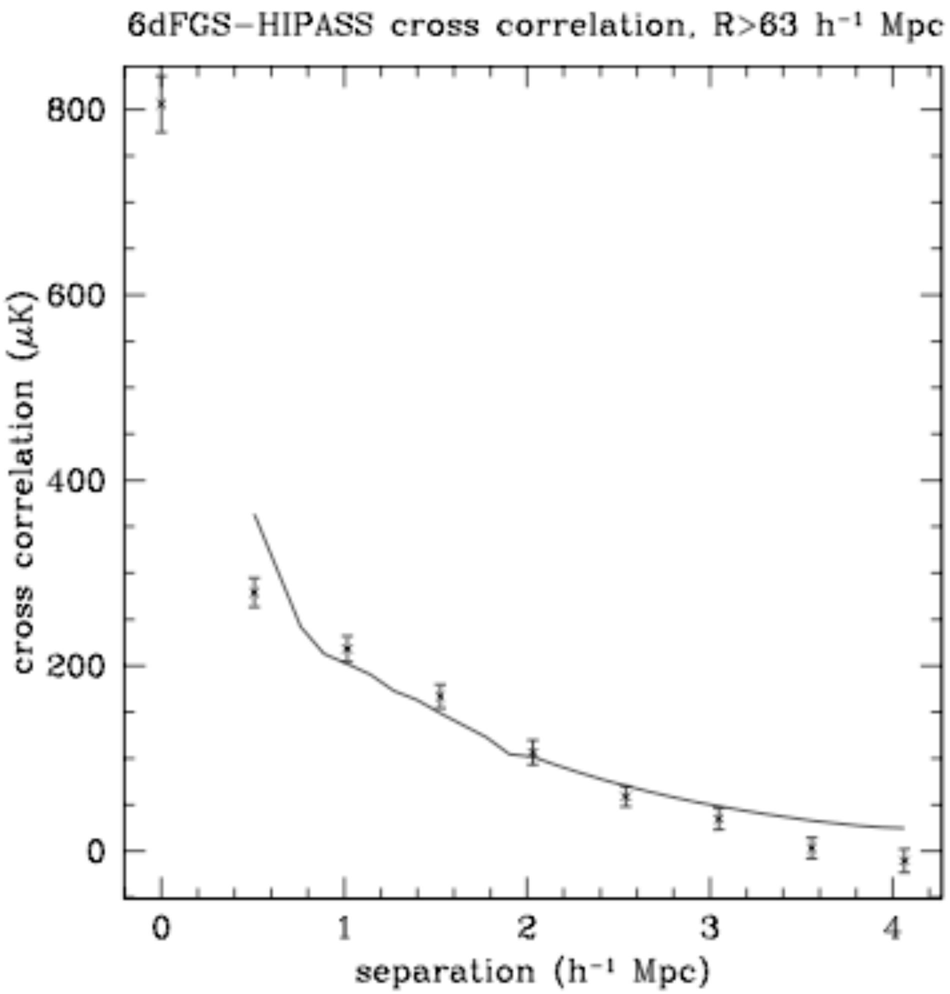


Figure 4. The correlation function of hydrogen 21 cm emission when stacked around optically selected galaxies from the 6dFGS. The solid line is a standard clustering model. The point at zero separation is the mean flux from 6dF galaxies, while points at larger separations measure the associated surrounding large scale structure. HI emission from the 6dF galaxies could spill up to 1 h^{-1} Mpc into neighboring bins at the $\sim 20\mu$K level.

- Show good correlation between Hydrogen and Optical galaxy surveys
- Neutral hydrogen traces Large-scale Structure well

What is Ω_{HI} at z=1?

Cross-correlating GBT HI & DEEP2 optical galaxies at z ~ 0.7-1.1

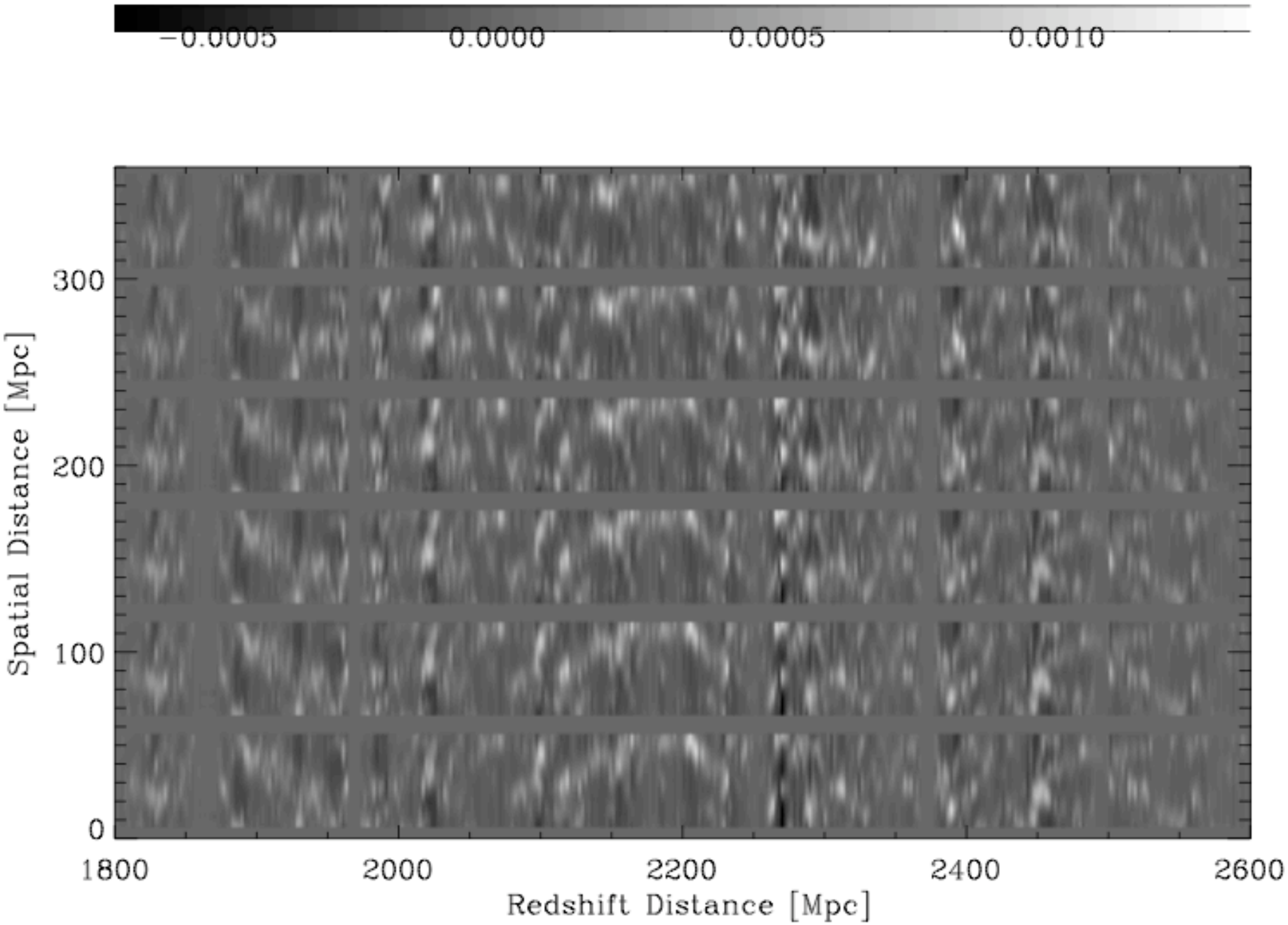
- GBT (Green Band Telescope): Observed at 660-900 MHz (df ~ 24 kHz), 0.7< z < 1.1, ~ 800 Mpc radially; Telescope beam ~15' ~10 Mpc at z=0.9
- DEEP2 Redshift Survey: Four 120' x 30' ~ 80 x 20 Mpc fields, each containing ~5000 galaxy redshifts (overlap with HI)
- Measure HI & optical cross-correlation on 10 Mpc (spatial) x 2 Mpc (radial) scales
    - Measure HI content & test of Intensity Mapping idea
- Measure

$$\zeta = \langle \Delta T_b \delta_{opt} \rangle = 300\, b\, r\, \delta_{opt}^2 \left(\frac{\Omega_{HI}}{10^{-3}}\right)\left(\frac{h}{0.73}\right)\left(\frac{\Omega_m + (1+z)^{-3}\Omega_\Lambda}{0.35}\right)^{-0.5}\left(\frac{1+z}{1.9}\right)^{0.5} \mu\mathrm{K}$$

Chang, Pen, Peterson, Bandura, submitted

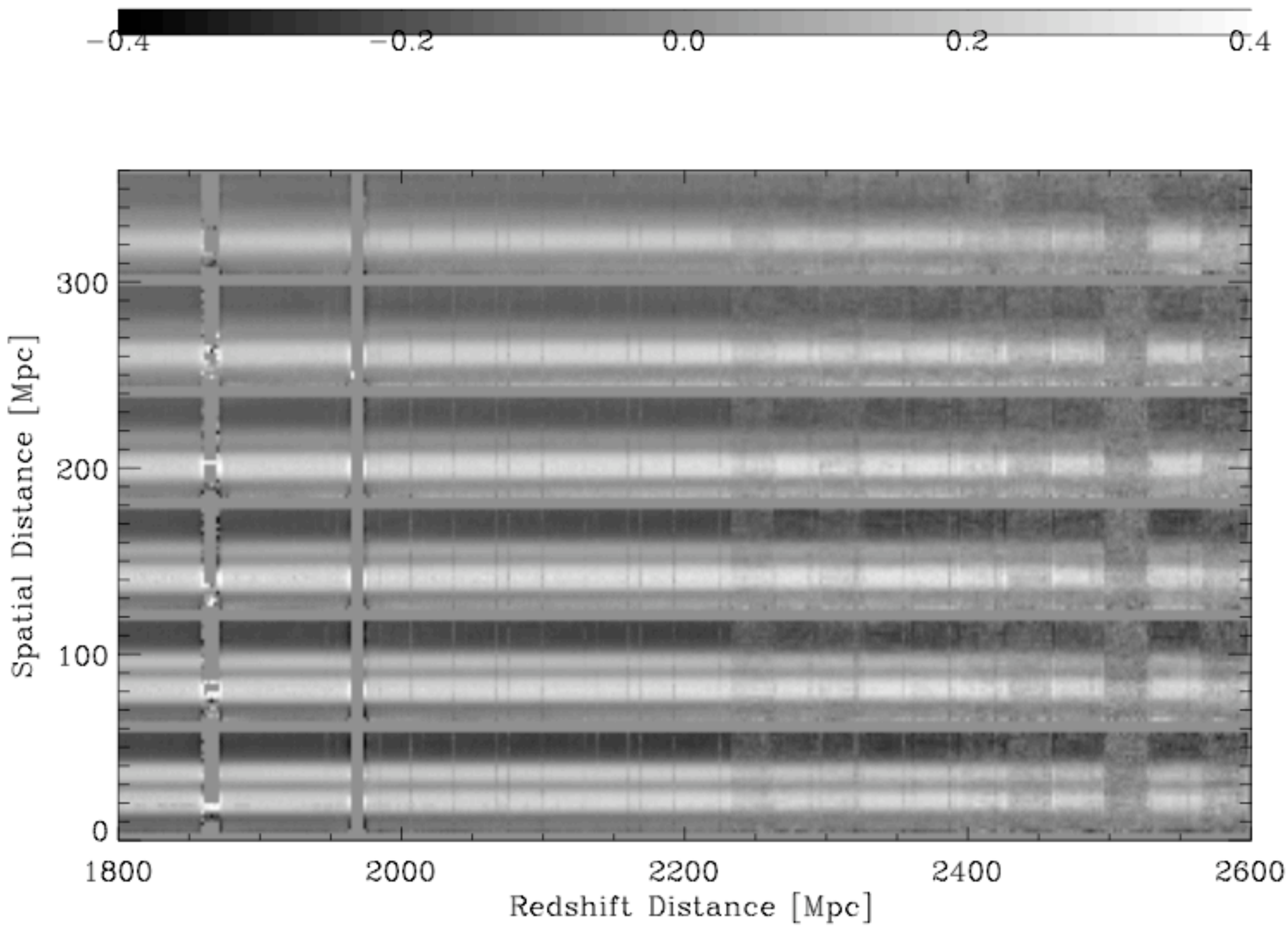
DEEP2 density field / HI simulation

- 2 x 2 x 2 Mpc pixels
- Spatially, 60 x 20 Mpc; 0.7 < z < 1.1



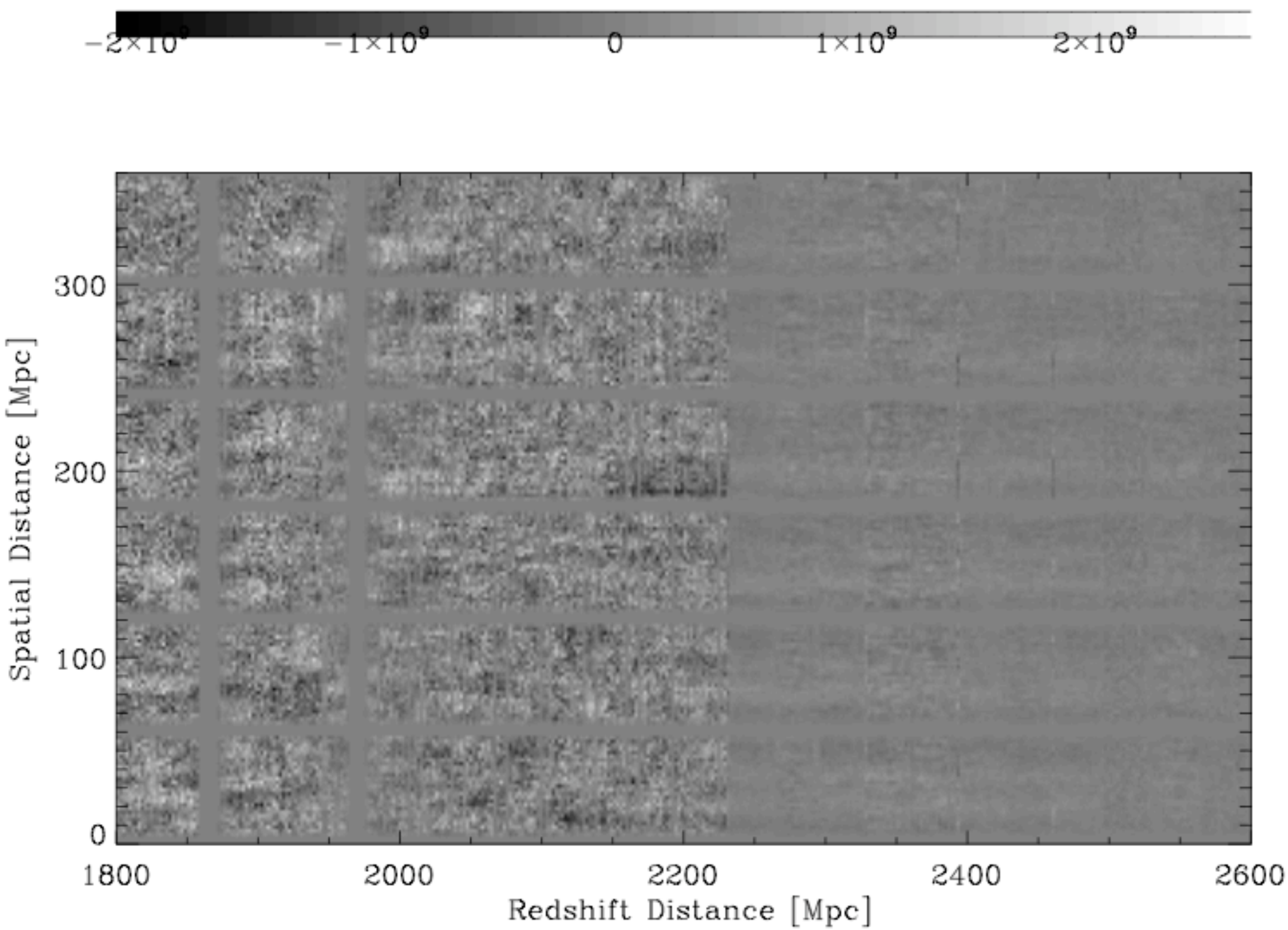
RFI Rejection

- Cross-polarization cuts; sigma-cuts remove high-level RFI



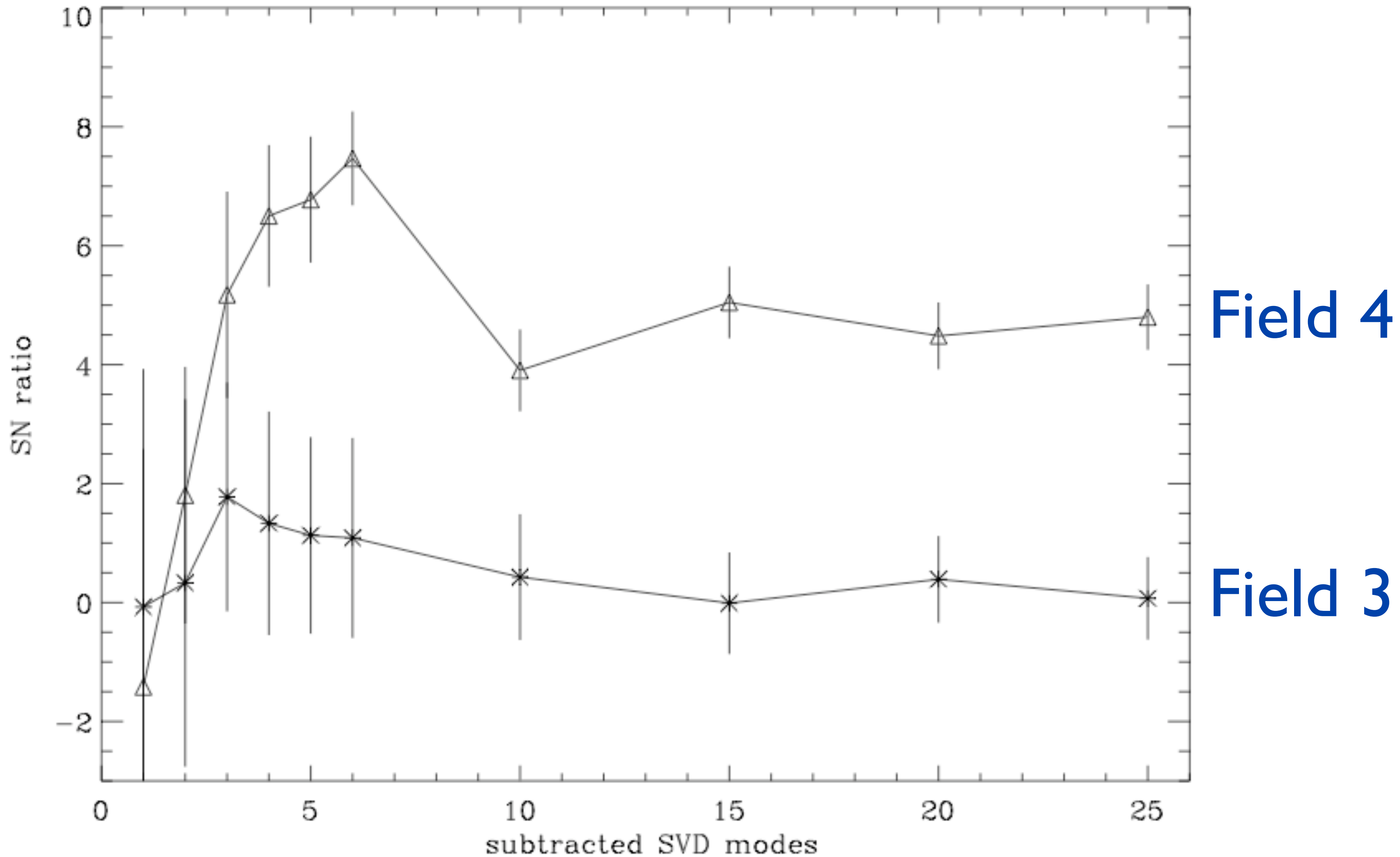
Foreground Subtraction

- Singular Value Decomposition (SVD) -- factor foreground as separable functions of space and z



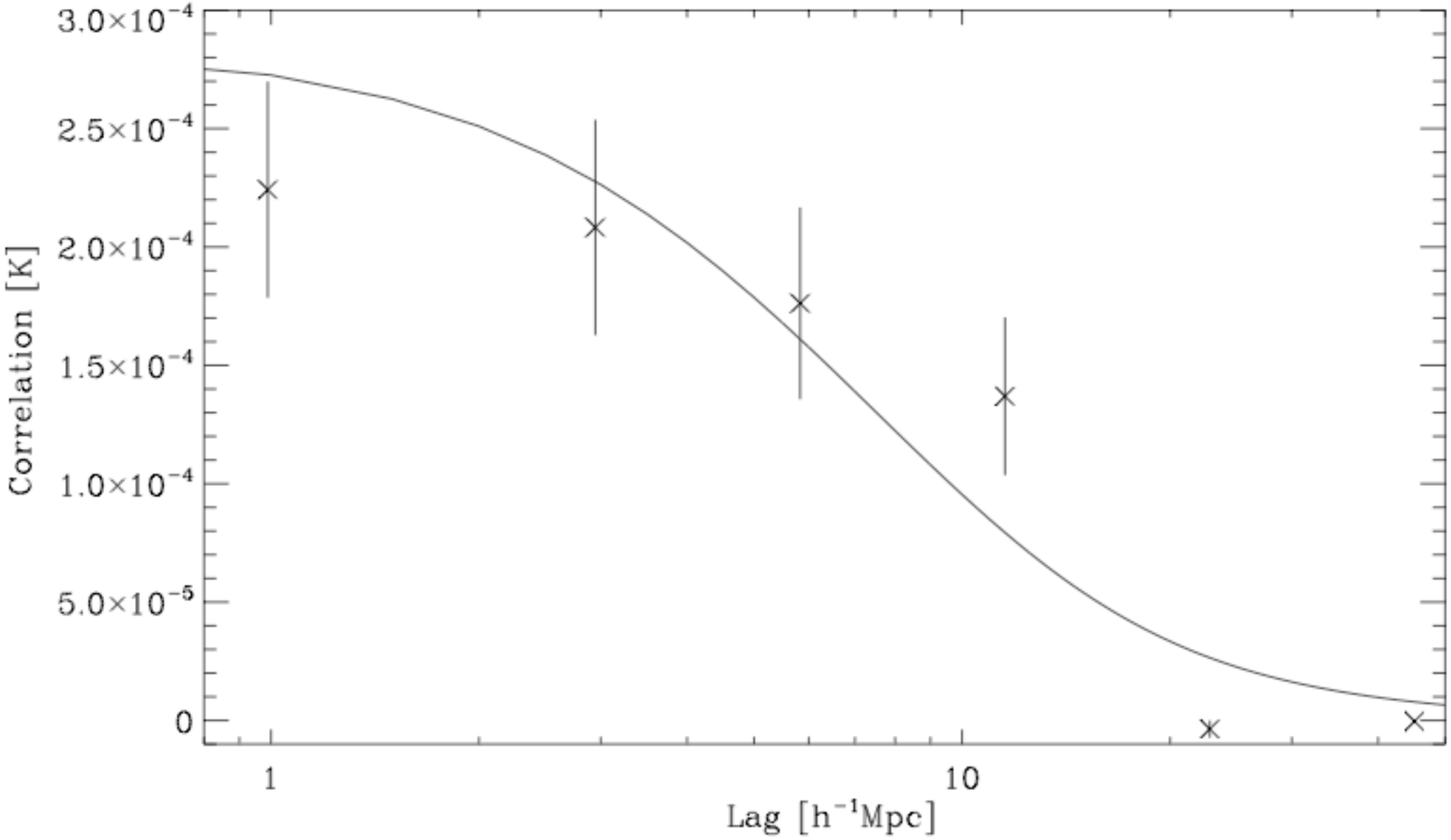
Impact of SVD on S/N

- Foreground contributes to correlation noise; SVD removes some signal;
- Use simulation to quantify loss of signal due to Foreground subtraction and analysis
    - Project Sims onto data SVD eigenmodes: ~30% loss
    - Measure S/N from data as function of SVD mode



HI & Optical cross-correlation at z~0.8

- Shows correlation between hydrogen and Deep2 optical galaxy surveys to 10 Mpc



Chang, Pen, Peterson, Bandura, submitted

Implications

- Cross-correlation temperature: 215 +/- 41 microK
- $\Omega_{HI}\ b \sim (7.2 \pm 1.3) \times 10^{-4}$
- Good amount of HI at z ~ 0.8
- Highest-z HI emission detection
- HI auto-correlation temperature ~1mK

Outlook

- 21cm line provides a good probe of cosmology
- HI Intensity Mapping: an efficient/economical way of measuring BAO/dark energy
  - Neutral hydrogen traces large-scale structure at low-z
    - HIPASS/6dF cross-correlation shows good correlation
  - Good amount of neutral hydrogen at z ~ 0.8
    - GBT/DEEP2 cross-correlation: $\Omega_{HI}\, b \sim (7.2 \pm 1.3) \times 10^{-4}$
  - Issues of foregrounds, RFI removal, calibration, etc.
    - Some insights, but still need lots of work
- Not entirely impossible!